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# A mathematical model for the optimal operation of the University of Genoa Smart Polygeneration Microgrid: Evaluation of technical, economic and environmental performance indicators

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ABSTRACT

The continuous spread of DER (Distributed Energy Resource) systems and CHCP (Combined Heat, Cooling and Power) technologies around the world highlights critical issues concerning the management strategies of such complex energy infrastructures. The concept of SG (Smart Grid) could be the solution to these problems even if nowadays there are not so many ongoing research and development applications that demonstrate the effective economic and environmental benefits consequent to exploiting smart grid technologies. Therefore, it is essential to develop, both in civil and industrial applications, smart grid/microgrid test-bed facilities where the synergy of new equipment, advanced management systems and ICT (Information and Communication Technologies) can determine advantages in terms of operational cost reduction, primary energy saving and $CO_2$ emission decrease.

The present paper describes the main components of the SPM (Smart Polygeneration Microgrid) of the Genoa University located at the Savona Campus. The paper is focused on a mathematical model developed to optimally manage the SPM in order to minimize daily operational costs. The optimal results are reported also pointing the attention on $CO_2$ emission reduction and primary energy saving consequent to the optimal operation of the SPM in comparison with the current reference scenario not based on the distributed generation.



## 1. Introduction

The present paper is focused on SG (Smart Grid)/Smart Microgrid topics [1–6] and, in particular, its main goal is that of highlighting the useful effect of the adoption of a smart grid/microgrid, based on renewable and CHP (Combined Heat and Power) technologies, in a University Campus [1,7].

First of all, it is important to remember that in the recent years, many projects and national regulations around the world have been developed to enhance the spread of distributed generation technologies and the development of smart grid pilot facilities [1,6]. As assessed by Clastres in Ref. [5], the development of smart grid technology has raised the possibility of reconciling targets for climate-change (by the reduction of $CO_2$ emissions), energy efficiency policies, and safety of systems and technology; furthermore, the integration of renewable energy sources, storage and plug-in electric vehicles in electricity systems is becoming more and more an important goal to be achieved [5,8,9]. As well described by Giordano et al. in Ref. [6], where the current development of such innovative generation systems in Europe is reported, a smart grid can be described as an upgraded electricity network enabling two-way information and power exchange between suppliers and consumers. One of the main advantages of DER (Distributed Energy Resource) systems, as assessed by Mehleri et al. in Ref. [10], is their installation close to or even inside the end-users facilities, determining low electricity transmission losses and producing heat to cover local heating demands.

On the other hand, the growing number of decentralized energy generators has an impact on the traditional regulation and control strategies adopted by DSOs (Distributed System Operators) to manage distribution grids.

In the aforementioned context, one of the aims of SG is to develop technologies and advanced management software in order to face the continuous spread of DER and CHCP (Combined Heat, Cooling and Power) generators in low voltage and medium voltage networks [3,11–13]. In this regard, as described by Bracco et al. in

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Ref. [1], many national and international projects are focused on the distributed generation and smart grid concept but there is need to determine solutions that can be deployed at full scale [4,9]. To achieve this goal it is not only necessary to invest on new lines and substations, but it is essential to make the overall electricity system smarter, focusing in particular on ICT (Information and Communication Technologies). As reported by Higgins et al. in Ref. [14], smart grid technology supports a wide range of applications in power systems, such as protection and automation of the distribution system and security. This implies the transition from the traditional vertical organization of the electric system to a more flexible and dynamic model, in which a great deal of new functionalities should be considered: dynamic load management strategies, active response mechanisms, real-time control of the distribution network, energy storage systems, and automatic measurements of energy consumption. As a consequence, the success of such a system is possible only if ICT solutions for real-time data acquisition, transportation and processing are adopted [15–17]. In this regard, in Ref. [17] Wang et al. propose a survey on the current state of research on the communication networks of smart grids, whereas Usman and Shami in Ref. [16] discuss on some of the major communication technologies applied to smart grids, and Gao et al. in Ref. [15] report a systematic review of communication/networking technologies and architectures.

It is clear that smart grid research projects throughout the world are focused on several issues that need to be investigated, as assessed by authors in Refs. [2,7,18–20]; the objective of these projects is to contribute to the re-definition of the energy system, by promoting the research of an electric, thermal and telecommunication infrastructure aligned to the expectations of the energy smart grid concept.

Furthermore, in literature many works are focused on methods developed to optimize the operation of smart grids, or more in general of distributed generation systems, over a certain time horizon [7,10,13,21–27].

The Smart Polygeneration Microgrid of the University of Genoa, located in the Savona University Campus [1,7,28], is the object of a set of research activities focused on different issues related to modeling and simulation, energy efficiency, new communication protocols and paradigms. The aim is both the definition of a possible deployment of private microgrids to reduce energy costs for consumers and the improvement of power quality and security, with particular focus on dealing and possibly solving also weaknesses and critical aspects of such architectures in order to facilitate their application.

The SPM (Smart Polygeneration Microgrid) includes a number of heterogeneous distributed generation units, such as gas microturbines, photovoltaic and CSP (concentrating solar power), integrated with storage devices (such as sodium–nickel batteries) on a low voltage distribution system. The SPM mainly aims to achieve two objectives: to produce clean energy for the University loads and to operate as a test-bed facility for research, testing and development of management strategies and power components. In particular, the system has been designed to allow the following activities:

- implementation and validation of algorithms to predict the production from renewable sources, with the help of forecasting tools;
- implementation and validation of methods for the optimal operation of storage systems and of dispatchable sources, on the basis of the information on renewable production gathered by the aforementioned algorithms, in order to make the system follow a day-ahead production schedule;
- power flow control at the interface with the external grid, in order to control the exchange of active and reactive power;
- storage of energy measurements in a centralized database, in order to check the actual correlation with the energy forecast over a long time period and to make available an extensive data set for further researches;
- testing of new "smart" power converters for improving the integration of renewable sources into the power delivery system.

The paper is organized as follows. Firstly, in Section 2 the state of the art and innovation of decision models for microgrids is reported. In Section 3 a brief description of the SPM is outlined. In Section 4 the mathematical model developed in order to determine the optimal daily operation of the SPM is described. Finally, in Section 5 the most significant results of the study are reported, analyzing the economic and environmental benefits consequent to the optimized management of the SPM.

## 2. Decision models for microgrids: state of the art and innovation

In the field of energy and environmental systems, decision analysis, modeling and optimization are very important issues to be taken into account [29], especially when dealing with renewable energy integration [30].

Generally, decision models can be used both for planning/design and for operational management purposes. Fazlollahi et al. [31] focus attention on multiobjective design/planning and assess that analyzing only one optimal solution with mono objective function is not sufficient for sizing the energy system. Analogously, Ahmadi et al. [32] present a comprehensive thermodynamic modeling and multiobjective optimization of a polygeneration energy system for the simultaneous generation of heating, cooling, electricity and hot water from a common energy source.

Hafez and Bhattacharya in Ref. [25] focus the attention on the optimal design, planning, sizing and operation of a hybrid, renewable energy based microgrid, while Mehleri et al. in Ref. [10] propose a model for the optimal design of distributed energy generation systems that satisfy the heating and power demand at the level of a small neighborhood.

In Ref. [33] the effects of uncertainties on natural gas and electrical energy prices on the decision to invest in distributed generation are explored, taking as a reference the case of a microgrid installed in California. Threshold fuel costs are derived for triggering investments in DG and it is highlighted how DG investment advantage is higher when taking into account uncertainties on natural gas prices (if compared with a purely deterministic approach) and further increases if flexibility in DG operation is considered. In addition, it is shown how even relatively low volatility in electric energy prices makes investments on DG more attractive. Quiggin et al. [34] focus their attention on the minimization of power fluctuation, by applying a linear programming algorithm to a simulated microgrid equipped with a mix of multiple renewable sources and storage. The considered time range is one year (discretized in time intervals of 1 h) and various effects on the energy balance are considered (grid scale, configuration and type of generators, storages and loads, possibility of demand response), with the goal of obtaining an indication of which renewable sources are best suited to a particular demand profile.

At the operational management level, Menon et al. [35] focus attention on the concept of smart grids that involves interdependence between the electrical, thermal and material flows, assess that control strategies are required for the optimal operation of modern grids, and study the optimal design of multi-node microgrids integrating heat pumps and cogeneration units considering optimal predictive control strategies.